

**LIFE ASSESSMENT OF COMBUSTOR LINER USING UNIFIED
CONSTITUTIVE MODELS**

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ABSTRACT

Hot section components of gas-turbine engines are subject to severe thermo-mechanical loads during each mission cycle. Inelastic deformation can be induced in localized regions leading to eventual fatigue cracking. Assessment of durability requires reasonably accurate calculation of the structural response at the critical location for crack initiation.

In recent years nonlinear finite-element computer codes have become available for calculating inelastic structural response under cyclic loading. Most of these, in keeping with an accepted practice in the elevated-temperature design community, partition nonlinear elevated-temperature material behavior into rate-dependent creep and rate-independent plasticity components. However, analytical studies of hot-section components such as turbine blades (McKnight, 1981) and combustor liners (Moreno, 1981) have demonstrated that the classical creep and plasticity methods do not always predict the cyclic response of the structure accurately because of the lack of the interaction between plasticity and creep behavior. Experimental results have shown that the interaction of elevated temperature is very significant and cannot be ignored (Corum, 1977; Kujawski et al., 1979; Pugh and Robinson, 1978; and Senseny et al., 1978).

Under the Hot Section Technology Project (HOST), NASA Lewis Research Center sponsored the development of unified constitutive material models and their implementation in nonlinear finite-element computer codes for the structural analyses of hot-section components (Ramaswamy et al., 1984 and 1985; and Lindholm et al., 1984 and 1985). These unified constitutive models account for the interaction between the time-dependent and time-independent material behavior. In eliminating the overly simplified assumptions of the classical material model, unified models can more realistically represent the behavior of materials under cyclic loading high-temperature environments. The purpose of this study was to evaluate these unified models with regard to their effect on the life prediction of a hot-section component. The component under consideration was a Pratt & Whitney gas-turbine-engine combustor liner. A typical

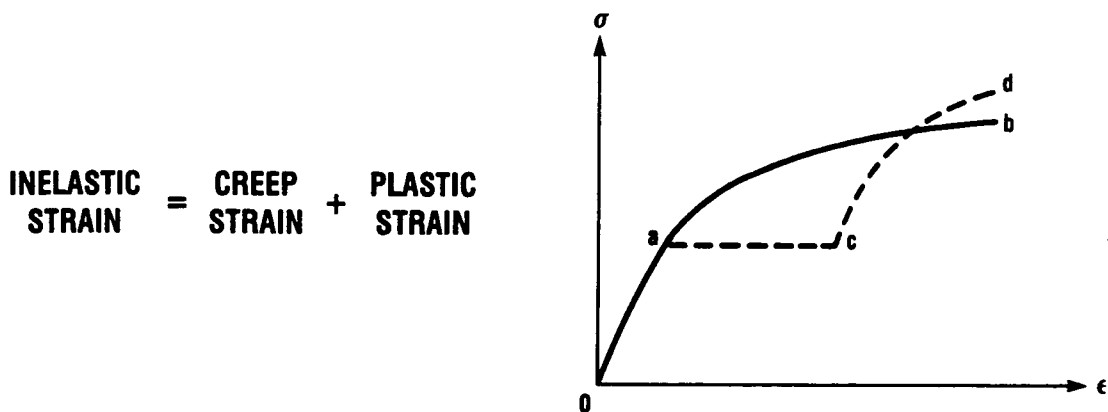
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engine mission cycle was used for the thermal and structural analyses. The analyses were performed at Lewis Research Center on a CRAY-XMP computer using the MARC finite-element code. Unified constitutive models of Bodner and Walker were used for the analyses. The results were compared with laboratory test results, in terms of crack initiation lives.

OVERVIEW

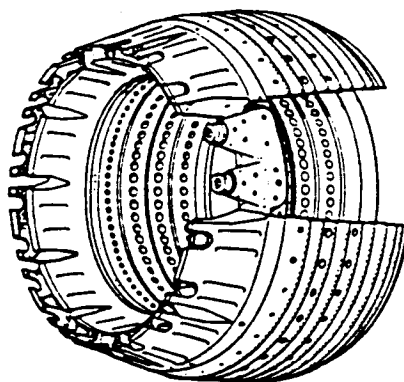
HARDENING EFFECT OF CREEP ON PLASTICITY

Life assessment of engine hot-section components requires a thorough knowledge of the thermal environment, accurate material characterization, calibrated failure data, and reasonably accurate calculation of the structural response at the critical location for crack initiation. In recent years, nonlinear finite-element computer codes have become available for calculating inelastic structural response under cyclic loading. Most of these computer codes are based on the classical inelastic methods. They partition nonlinear, elevated-temperature material behavior into rate-dependent creep and rate-independent plasticity components. In other words, inelastic strains are decoupled and formulated independently for the creep and plasticity portions, as illustrated in the left figure. However, analytical studies of hot-section components such as turbine blades (McKnight, 1981) and combustor liners (Moreno, 1981) have demonstrated that the classical creep and plasticity methods do not always predict the cyclic response of the structure accurately because of the lack of the interaction between the plasticity and creep behavior. Experimental results have shown that the interaction at high temperature is significant and cannot be ignored (Corum, 1977; Kujawski et al., 1979; Pugh and Robinson, 1978; and Senseny et al., 1978). The interaction is illustrated in the figure, wherein two loading paths are indicated by o-a-b and o-a-c-d. In the second loading path the applied stress is held constant between a and c, which results in creep deformation. As a consequence of the accumulated creep strain, c-d may appear to be stiffer than a-b for a creep hardening alloy. Creep softening alloys would exhibit a less stiff response.



ANNULAR COMBUSTOR LINER

Under the Hot-Section Technology Project (HOST), NASA Lewis sponsored the development of unified constitutive material models and their implementation in nonlinear, finite-element computer codes for the structural analyses of hot-section components. These unified constitutive models account for the interaction between the time-dependent and time-independent material behavior. In eliminating the simplified assumptions of the classical material model, unified models should more realistically represent the behavior of materials under cyclic loading and high-temperature environments. In an application of the unified material constitutive models, life assessment of a Pratt & Whitney gas turbine engine annular combustor liner (as shown below) was conducted. Unified constitutive models of Walker and Bodner were used. The results were compared with laboratory test results, in terms of crack initiation lives.



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POSTER PRESENTATION

CLASSICAL MATERIAL CONSTITUTIVE MODEL - DECOUPLED STRAINS

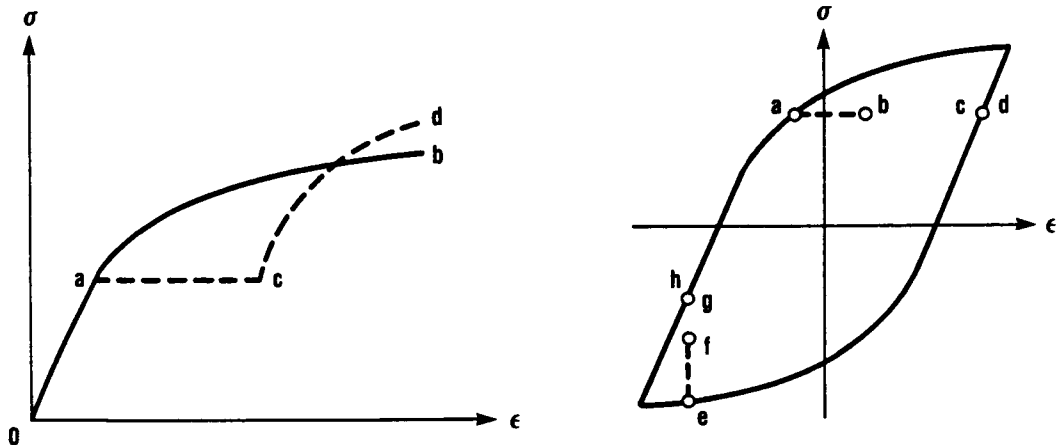
Conventionally, the most widely used constitutive description of metals at high-temperature employs the time-independent classical theory of plasticity to characterize short-term deformation, while relying upon time-dependent classical theory of creep to characterize long-term deformation. The total strain, or strain increment, then, consists of four additive contributions - elastic, plastic, creep, and thermal components. In other words, constitutive equations are decoupled and formulated independently for the elastic-plastic, creep, and thermal portions. Although the classical theories of plasticity have been used quite extensively to characterize the behavior of metallic structures at room temperature, it does not necessarily justify their applicability to other loading conditions such as high-temperature environment. Analytical studies of engine hot section components such as turbine blades and combustor liners have demonstrated that the classical theories do not always predict the cyclic response of the structure accurately. For high-temperature applications the most severe shortcoming of classical theories is that the interaction between creep and plasticity is not adequately taken into account. Experimental results have shown that the interaction at elevated temperature is significant and cannot be ignored.

$$\text{INELASTIC STRAIN} = \underbrace{\text{CREEP STRAIN} + \text{PLASTIC STRAIN}}$$

CLASSICAL UNCOUPLED

CREEP-PLASTICITY INTERACTION

Two types of creep-plasticity interactions are generally observed. First, accumulated creep strain has a hardening effect on subsequent plastic response. This phenomenon is shown in the left figure, wherein two loading paths are indicated by o-a-b and o-a-c-d. In the second loading path the applied stress is held constant between a and c, which results in creep deformation. As a consequence of the accumulated creep strain, c-d appears to be stiffer than a-b. Second, recent history of plastic strain has significant influence on subsequent time-dependent behaviors. In the right figure, a-b and c-d represent creep strains corresponding to creep tests performed at loading and unloading branches, respectively, but at the same stress level. While the former undergoes a significant amount of creep deformation, the latter shows virtually no creep. The same kind of phenomenon is also observed when relaxation tests are conducted as designed by e-f and g-h in the right figure.



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UNIFIED MATERIAL CONSTITUTIVE MODELS

In light of the previous discussion, it is apparent that effort must be made to improve the prediction of inelastic behavior of metals at high temperatures. The new theories toward characterization of material behavior at high temperatures are known as unified theories in the sense that plastic and creep strains are represented and treated by a single kinetic equation and a discrete set of internal variables. They are also known as viscoplastic theories because they are capable of modeling both rate-dependent and rate-independent behaviors.

$$\begin{aligned}\dot{\sigma} &= E(\dot{\epsilon} - \dot{\epsilon}^I - \dot{\epsilon}^{TH}) & \dot{\alpha} &= h_{\alpha} \dot{\epsilon}^I - r_{\alpha} \\ \dot{\epsilon}^I &= f \left[\frac{\sigma - \alpha}{K} \right] & \dot{K} &= h_K |\dot{\epsilon}^I| - r_K\end{aligned}$$

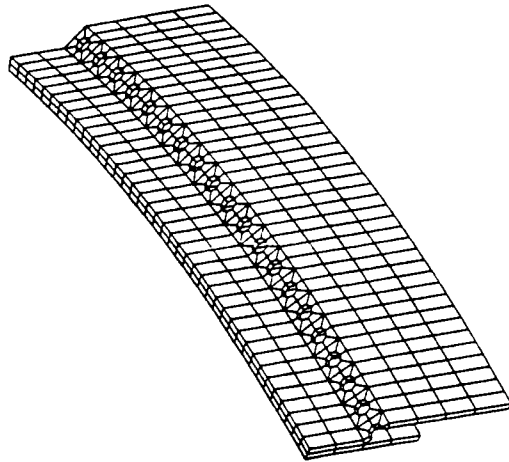
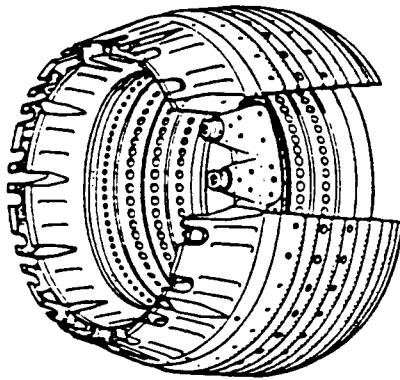
WHERE

h_{α}, h_K STRAIN HARDENING FUNCTIONS
 r_{α}, r_K RECOVERY FUNCTIONS
 α, K STATE VARIABLES
 ϵ^I INELASTIC STRAIN
 ϵ^{TH} THERMAL STRAIN
 σ STRESS

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COMBUSTOR LINER AND ITS FINITE ELEMENT MODEL

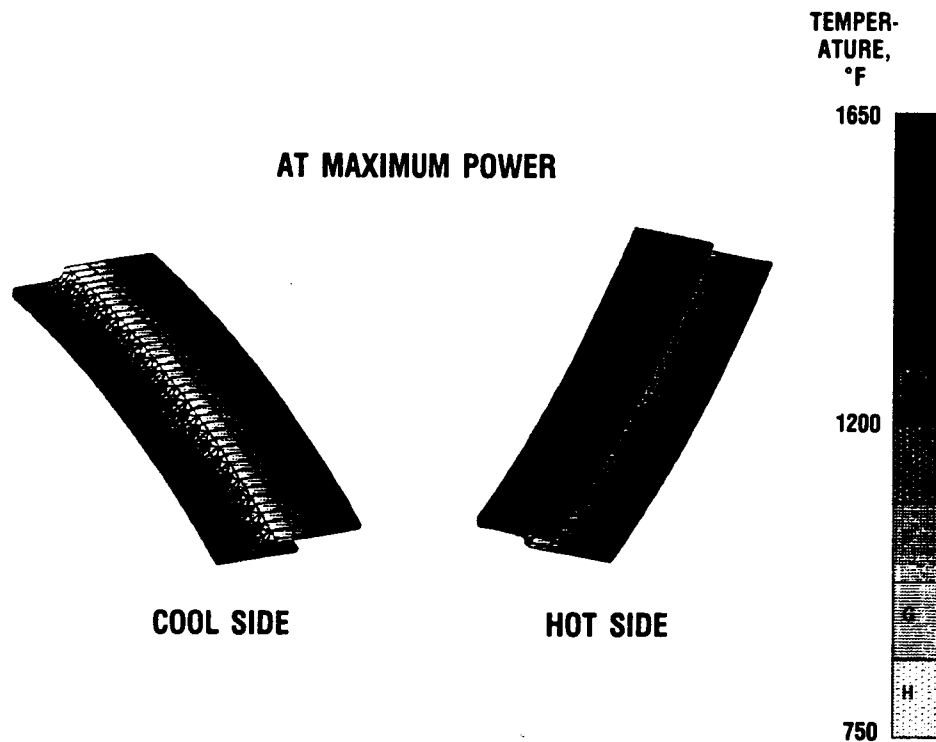
In an application of the unified material constitutive models, life assessment of a Pratt & Whitney gas-turbine-engine annular combustor liner was conducted. The liner is air-cooled and is made of Hastelloy-X alloy. The finite-element model has 546 elements and 1274 nodes. Eight-node solid elements were used. Because of symmetry only a section of the liner was modeled.



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THERMAL ANALYSIS OF ANNULAR COMBUSTOR LINER

Thermal analysis was first conducted to determine the temperature distribution of the combustor liner. These temperatures were later used for the structural analysis of the liner. A typical engine mission cycle was used for the analysis. Temperature histories at the combustor liner critical locations were also determined.



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COMPARISON WITH TEST RESULTS

Subsequent nonlinear structural analysis of the combustor liner was performed. The analysis was conducted with the unified constitutive models of Walker and Bodner (Lindholm et al., 1984 and 1985). Both models were implemented into the MARC finite-element code. Stress and strain ranges at the liner critical locations were determined.

The total strain and inelastic strain ranges were used for the life assessment of the combustor liner, based on the experimental results by Jablonski (1978). In conjunction with the analyses, laboratory tests were performed on the combustor liner. Comparisons were made of crack initiation lives. Good agreement between predicted and measured life was obtained.

ANALYTICAL METHOD	MECHANICAL STRAIN RANGE, %		PREDICTED LIFE, CYCLES
	TOTAL	INELASTIC	
UNIFIED (WALKER)	0.587	0.315	1000 TO 1500
UNIFIED (BODNER)	.580	.270	1000 TO 1500

OBSERVED LIFE = 1603 CYCLES

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REFERENCES

- Corum, J.M., 1977, "Evaluation of Inelastic Analysis Methods," Transactions of the 4th SMIRT Conference, San Francisco, Vol. L, Paper L.
- Jablonski, D.A., 1978, Fatigue Behavior of Hastelloy-X Elevated Temperatures in Air, Vacuum, and Oxygen Environments. Ph.D. Thesis, University of Connecticut.
- Kujawski, D., Kallianpur, V., and Krempl, E., 1979, "Uniaxial Creep, Cyclic Creep and Relaxation of AISI Type 304 Stainless Steel at Room Temperature, An Experimental Study," RPI Report CS 79-4.
- Lindholm, U.S., Chan, K.S., Bodner, S.R., Weber, R.M., Walker, K.P., and Cassenti, B.N., 1984, "Constitutive Modeling for Isotropic Materials," NASA CR-174718.
- Lindholm, U.S., Chan, K.S., Bodner, S.R., Weber R.M., Walker, K.P., and Cassenti, B.N., 1985, "Constitutive Modeling for Isotropic Materials," NASA CR-174980, 1985.
- McKnight, R.L., Laflen, J.H., and Spamer, G.T., 1981, "Turbine Blade Tip Durability Analysis," NASA CR-165268.
- Moreno, V., 1981, "Combustor Liner Durability Analysis," NASA CR-165250.
- Pugh, C.E., and Robinson, D.N., 1978, "Some Trends in Constitutive Equation Model Development for High-Temperature Behavior of Fast-Reactor Structural Alloys," Journal of Nuclear Engineering and Design, Vol. 48, pp. 269-276.
- Ramaswamy, V.G., Van Stone, R.H., Dame, L.T., and Laflen, J.H., 1984, "Constitutive Modeling for Isotropic Materials," NASA CR-17485.
- Ramaswamy, V.G., Van Stone, R.H., Dame, L.T., and Laflen, J.H., 1985, "Constitutive Modeling for Isotropic Materials," NASA CR-175004.
- Senseny, P.E., Duffy, J., and Hawley, R.H., 1978, "Experiments on Strain Rate History and Temperature Effect During the Plastic Deformation of Closed-Packed Metals," ASME Journal of Applied Mechanics, Vol. 45, pp. 60-66.